HUMAN FACTORS ISSUES IN THE DESIGN OF GROUND SYSTEMS: A PATHFINDER ACTIVITY

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ABSTRACT

In his article *Ground Systems Testing*, N. Strang stated the following: "Ground systems represent the largest overall cost for most space programs. However, testing of ground systems does not always get the same visibility as vehicle testing, for example. This is a major concern because problems with ground systems are just as likely to cause a mission failure as are vehicle problems. Also, ground systems tests are more prone to human error…" [1]

Based on many years of experience in aviation maintenance, spacecraft processing, and launch vehicle processing, a core team of ten human factors researchers and practitioners initiated a Pathfinder Activity to improve Kennedy Space Center (KSC) designs through the optimization of ground and flight crew interfaces with ground systems (GS) and ground support equipment (GSE) for the Constellation Program. This team of government and non-government personnel came together because they are passionate about proactively improving the safety of ground operations by incorporating Human Factors engineering principles in the designs of Constellation ground systems and ground support equipment (GS/GSE). This self-directed team consisted mostly of volunteers and overcame significant obstacles to demonstrate the value of infusing human factors engineering in KSC systems engineering functions and processes.

Because a number of GS/GSE Design Teams were still at the early stages, the intent was to demonstrate how to review and influence designs. Several factors converged to support this effort including: 1) the existence of ten years of mishap data that underscored the cost of ground operations mishaps and the contribution of human factors issues that could have been mitigated through better designs; 2) the relevance of newly drafted Human-System Integration Requirements; and 3) the willingness of nine GS/GSE Design Teams (7 mechanical systems, 1 fluid system and 1 electrical system) to participate in a Human Factors Engineering Design Evaluation. A two-hour overview was developed to familiarize ground system designers with basic human factors principles. Participant Design Teams then filled out an evaluation worksheet that queried the teams on topics such as: workspace, tool clearances, visual access, displays, damage/error prevention, detection and recovery, etc. Each of the Design Teams then participated in separate two-hour working sessions in which descriptions of the system and applicable human factors issues were discussed in detail.

The expected outcome is ground systems that are safer and easier (and therefore cheaper) for ground crews to operate and maintain during 20+ years of Constellation launch operations. Flight crew safety will also be enhanced due to reductions in risks of undetected ground crew errors and/or collateral damage incurred during ground operations.

The Human Factors Pathfinder Activity continues to have a significant positive impact on GS/GSE Design Teams. Examples are listed below:

- Many specific design changes have already been baselined or are in work, resulting in GS/GSE designs that are safer and easier for ground crews to use.
- Human factors evaluations completed during the pathfinder have been used by several teams to support 30% design reviews.

- Core team members have supported design reviews and provided additional design recommendations after the Pathfinder Activity.
- The KSC Engineering Directorate is exploring the acquisition of human factors engineering expertise to embed in GS/GSE Design Teams.
- The core team developed a workbook for GS/GSE designers that has been widely distributed and will be a primary input to a chapter in a new Engineering Design Handbook devoted to human factors.
- By providing a "Human Factors Overview for GS/GSE Designers" as a KSC Engineering Academy event, awareness of potential human factor issues has been raised, even in Design Teams that were not able to directly participate in the Pathfinder Activity.
- The KSC Engineering Directorate is developing a Human Factors Plan for additional Design Teams, including human factors for software and computer/console systems (human-computer interaction).
- The Constellation Ground Operations Project Office is infusing human factors in the Ground Operations Planning Document using pathfinder examples and other materials.
- The Constellation Ground Operations Project Office is refining specific Level 3 human factor requirements for ground systems that complement the requirements for "ground assembly and maintenance" in the Level 2 Human System Integration Requirements (HSIR) document [2].
- The GSE design standard (NASA STD 5005) was improved by using the FAA Human Factors Design Standard as the basis for human factor requirements.

1. INTRODUCTION

As in other high-risk, complex operations, ground systems supporting space missions of the future consist of systems of technologies and processes whose design and development must incorporate safeguards from operational risks. Ground crew operations are major cost and risk drivers that impact all elements of NASA’s safety hierarchy. Thus, when considering safety, sustainability, and affordability goals, ground elements must be part of the design and operational decision process, and leveraged by appropriate human-systems integration. Ground operations include tasks that are hazardous, tedious, complex, and physically and mentally demanding. A functional breakdown of key activities in ground operations described by Barth and Kanki [3] includes:

- Manufacturing and acquisition systems
- Stand-alone vehicle and payload processing
- Integrated vehicle and payload processing
- Launch and mission control
- Landing and recovery
- Repair and refurbishment
- Enabling operations such as integrated logistics, ground crew training, planning, and scheduling

While the designers of future ground systems do not have available the detailed descriptions of operational processes, training requirements, procedures, that have not yet been developed, they can benefit from current operations because they are similar in critical ways.

1.1. Shuttle Ground Operations Mishap Data

From an analysis of 335 mishaps in shuttle ground operations from November 1996 to September 2007 **(**United Space Alliance Industrial and Human Engineering Office, Internal Report, October 2007), a variety of causes and contributing factors were identified including team behaviors, procedures, decision process, training, individual attitude, task experience, supervisory controls, culture and policies, and design issues. While only one of many factors, design issues contributed in 23% of 1254 factors cited.. When design issues were further categorized, they divided into 73% ground systems design as opposed to 27% flight systems design. In short, evidence indicates that attention to design issues can prove to be a proactive deterrent to the risk of mishap.

In addition to the safety cost of mishaps, there are direct costs to be considered. For example, for 11 NASA/KSC mishap investigations boards in FY06 and FY07, $3.5M in direct costs included civil service labor and travel, board procurement costs and estimated hardware damage costs. This did not include contractor labor for investigation and corrective actions, indirect costs, schedule impact and personal injuries.

1.2. Human-Systems Integration Requirements

An opportunity exists during the current phases of NASA’s Constellation Systems to influence the designs of new flight and ground systems through development and implementation of ground crew requirements, standards, guidelines, and through active participation in design reviews by human factor experts.

Flight systems include vehicles and payloads. Flight/ground system interfaces include fluid umbilicals, flex hoses, mechanical connectors, and electrical connectors. A new section in the Human-Systems Integration Requirements document (Section 3.9, Ground Maintenance and Assembly) focusing on ground crew factors was recently added [2]. The challenge to design a flight vehicle that is safe and easy for flight crews to fly, as well as safe and easy for ground crews to work on was given to the Constellation Human Factors Systems Integration Group and systems engineering offices across the Constellation Program.

2. PATHFINDER ACTIVITY

Our distributed 10-menber core team spent a few months preparing materials (workbook and worksheets) and general format for the main activities of the Pathfinder Activity which took place during one week in November 2007: namely, a two-hour Human Factors Overview for Ground Systems/Ground Support Equipment (GS/GSE) Designers, working sessions with Design Teams and a wrap-up session with Design Team Leads.

2.1. Development of Materials

Workbook. A nearly 150-page workbook was prepared that would serve as a backup document for the Design Team working sessions, providing detailed explanations and additional examples to illustrate the human factors to be considered for each GS/GSE design. In addition to being a supplement to the worksheet, it also provided sections on human factors principles, discussion of other human factors tools and methods, and trade studies. Since the Design Teams were all supporting the new Constellation program, the materials were made to be as consistent with emerging Constellation requirements as possible at the time. Areas of focus matched the Worksheet topics listed in the next section.

Worksheets. The worksheets started with a blank section for the Design Team to fill in a brief description of the ground system/ground support equipment (GSE) they were designing. Next, for each human factor consideration listed, the team was to check a box for applicability and briefly describe potential human factor challenges related to the ground system/GSE they were designing. For example, if their GS/GSE did not involve Personal Protective Equipment or a Control Room in any way, they could check "not applicable." But the point of the worksheet was to get teams to carefully think about each of the following issues.

1. *Work Envelope Volume* (e.g., design is limited in granting minimum access needed to remove, relocate, and replace flight and ground hardware)
2. *Tool Clearances* (e.g., design does not allow enough space to use required tools for removal of components during maintenance tasks)
3. *Functional Work Areas* (e.g., design does not separate functions or activities that could conflict with each other during processing, maintenance, or inspection tasks)
4. *Visual Access* (e.g., design has visual access openings located beneath or behind components that restrict visibility)
5. *Displays Within Field of View* (e.g., design has displays that are not in the direct line of sight during maintenance, inspection, or processing tasks)
6. *Interface Controls and Information Displays* (e.g., design does not provide clear, functional identification for each control, indicator, connector, and test point)
7. *Lifting, Pushing & Pulling* (e.g., components weighing over 40 kg (85 lbs) that require removal/installation do not have lifting points for hoists or other lifting devices)
8. *Connectors* (e.g., design allows mis-mating of connectors during ground operations)
9. *Interfaces* (e.g., equipment labels do not have standardized locations and markings)
10. *Personal Protective Equipment (PPE)* (e.g., ground operation allows for required PPE to be worn during called out tasks but may not account for mobility of technician)
11. *Control Rooms* (e.g., control room design does not allow for easy communication/interface with outside teams during some operations)
12. *Damage/Error Prevention* (e.g., design has limited capability to prevent human errors and human-induced collateral damage)
13. *Environment* (e.g., design does not account for tasks that will be completed outdoors or in other challenging work environments)
14. *Consistent Work Practices* (e.g., procedures and training for ground systems/GSE are not offered in a standardized format)
15. *Damage/Error Detection* (e.g., design does not allow all types of potential collateral damage induced during ground operations to be detectable by inspection or test)
16. *Damage/Error Recovery* (e.g., design has limited capability for recovering from human errors or human-induced collateral damage)

2.2. Human Factors Overview

A two-hour panel discussion was designed to familiarize our targeted audience (fluid and mechanical systems designers) with basic human factors principles as a pre-requisite for their working sessions. Thus, it was tailored to apply specifically to the design of ground system and ground support equipment. The core team felt that the following elements should be incorporated in the four panelists' presentations:

- Goals and Background including KSC mishap data and examples
- Historical Perspective in aviation and space safety
- Design Topics and Examples covering each main topic area in their workbook and worksheet
- Shop Floor Perspective including specific application examples

The Human Factors Overview was conducted through the Kennedy Engineering Academy (KEA) whose support in announcing the event, supporting it technically and logistically, and conducting a post-event feedback survey was invaluable. More than 100 attendees came to the event thus expanding the reach of the Pathfinder Activity far beyond the participating Design Teams. This provided the additional benefit of generally increasing human factors awareness and helping to explain the purpose of this effort to managers, supervisors, and other Engineering organizations outside the targeted group.

Survey feedback administered by the KEA on 7 questions pertaining to the Human Factors Overview averaged 4.3 on a 5-point scale (where 0 reflected zero value and 5 reflected high value). Things that were most liked included: specific design examples, application of human factors principles to GSE designs, the varied perspectives of speakers, looking at life cycle and the use of Integrated Product Teams, user input to designs, designing with users in mind, Human Factors Specialist as part of the Design Team, and the worksheet was a useful handout. Suggestions for improvements or additions included: incorporate the issues in design approval/reviews, develop Human Factors Specifications, develop human factors for software systems, and provide overview of design visualization tools.

2.3 Design Team Sessions

Nine Design Teams participated including 7 mechanical systems, 1 fluids system and 1 electrical system:

1. Upper Stage T-0 Tilt-Up Umbilical Arms
2. Upper Stage Umbilical Plates
3. Mobile Launcher Physical Data Interface (electrical)
4. Emergency Egress System
5. Crew Access Arm
6. Mobile Launcher Access Platforms
7. Mobile Launcher Hypergol Servicing System (fluids)
8. SRB Forward Skirt Umbilical
9. First Stage Aft Skirt Umbilical

Most of these Design Teams were at approximately the 30% Design Review. This proved to be a good time to start this activity since the designs were developed enough to evaluate with respect to human factors, but not so locked into designs that they could not be changed.

Each group met separately for 2 hours that began with a 15-20 minute overview of the current design by the Team Lead. While somewhat laborious for the Design Team, these overviews, usually complete with drawings and data, were extremely well presented, and contained crucial information for the Human Factors core team to understand the details of the design functions, issues and future operational use. The Design Team also presented their responses to the worksheet as the starting point for discussion of each of the 16 issues on the worksheet (See Tables 1a and 1b for examples).

In addition to a facilitator for each session, members of the core team provided support to the discussion and took notes that would complete the worksheets. Some teams had a natural ability to quickly see the human factors issues more easily than others. It became clear over the course of the sessions that various perspectives such as Safety and Mission Assurance, Technician, Human Factors Engineer and Systems Engineer, could enable Design Teams to more readily see some of the potential human factors design issues. For example, if a Design Team had a team member that had operational experience as a technician, they would have an easier time keeping the end user in mind (e.g., *Tool Clearances, Visual Access, Damage Prevention, Consistent Work Practices*). If they had a Systems Engineer on the team, they might be more inclined to think of *Connector* or *Interface* issues.

2.4 Design Team Leader Wrap-up

Five of the Design Team Leads participated in the Wrap-up session. On a 5-point scale (where 0 reflected zero value and 5 reflected high value), the average score was 4.0. The primary issue brought up was that of continued support. While they found the session helpful, they felt that having human factors expertise embedded in the team would be the most effective approach. Other emergent issues included the following:

- Adequate tie-off/attach points for high crew operations at the pad
- Adequate integration/communication of requirements and design trades with other design teams
- Increased technician participation in design teams
- Design team activities to increase understanding of the hands-on user perspective (e.g., trying on Self Contained Atmosphere Protective Ensemble (SCAPE) suits, interviewing current operators)

Table 1a: Examples of Design Team Worksheet Entries

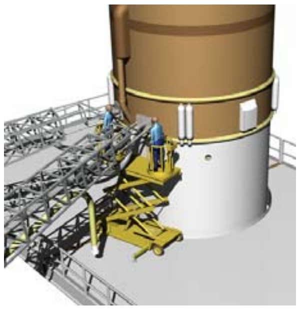
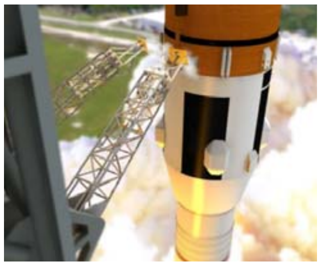
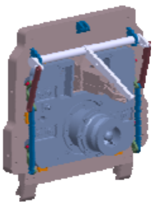
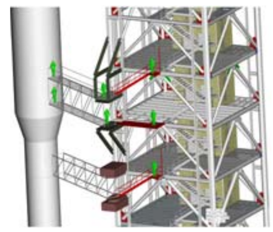
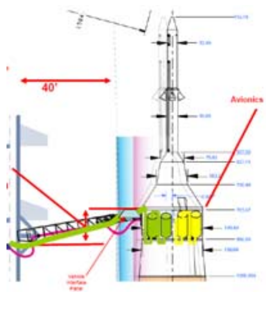
EXAMPLES		
Human Factors Challenges	**Recommendations and Potential Design Solutions**	
Upper Stage T-0 Tilt-Up Umbilical Arms (TUUA)		
Damage/error prevention – need reliable system feedback when technician lowers arm and mates the umbilicals. - Umbilical placement and mating operation is a precision operation requiring two technicians; a mistake during the mating operation could cause incapacitating damage to the vehicle.	Procedural Recommendation: Have one technician run the motor to lower umbilical to a marked position. Use lock- out pins so umbilical can't go below horizontal position and so the umbilical end does not over-extend and damage the vehicle. - Include a systematic analysis of VAB processing tasks for potential process escapes/catches (using HF-PFMEA or a similar method) and usability testing/ evaluation using the prototype in the LETF to satisfy the requirement for a human factors assessment	 
Work envelope – ground plate to flight plate interface is only accessible by platforms in VAB (no on-pad access). Potentially limited platform area during mating operation.	Coordinate platforms used for vehicle access so they can also be used for maintenance and inspection of umbilical components and subsystem replacement items in nominal and vertical positions. Consider designing custom access platforms.	
Lifting, pushing, and pulling - ground plate movement into mating position may require heavy exertion from technicians**.**	Use lift assisting devices and guides to keep physical forces within recommended weight limits and protect from inadvertent, sudden arm movements. Provide carts to transport and maneuver air tuggers if VAB shop air is used.	
. Upper Stage Umbilical Plates		
Connectors – if not connected properly, requires roll-back to VAB. Limited space is available on the plate to access connectors.	Consider a trade study on number of guide pins or a custom alignment tool. Extend crows feet to reduce the mating angle and use a centering feature. Consider self-alignment approaches, a laser alignment system, and/or a linear mating system (vs angled mating system).	**Nov 07 baseline**   **Feb 08 baseline**
Damage/error prevention and detection - to avoid connect/engagement overrun	Provide a visual indication on the collet engagement so that it is not overrun but fully connected. Need verification that feet are properly seated.	
Note: in the Feb 08 baseline: *a "linear engagement after angular mate" design with centering feet used. Alignment pins were eliminated*		
Mobile Launcher Physical Data Interface (MPDI)		
Work envelope – cable congestion.	Increase spacing between connectors within and between panels. Consider locations of connectors on panels compatible with procedural sequence (start with inside connectors; work out to edge.). Make most used connections most accessible.	
Functional work areas – high or low connections.	Consider using a horizontal configuration of smaller panels to reduce above-the-head or below-the-waist connections.	
Damage/error prevention and detection – mismates, misalignments**.**	Color coding and labeling of cables with large, bold fonts. Consider built-in lights for the MLP, possibly LED. Reduce/eliminate blind con-nections. Use keyed connectors. Provide visual and/or audible feedback for good connections.	

Table 1b: Examples of Design Team Worksheet Entries

EXAMPLES		
Human Factors Challenges	**Recommendations and Potential Design Solutions**	
Mobil Launcher Access Platforms		
Work envelope and access – suited personnel have limited access, mobility, peripheral vision, etc.	Use mezzanine elevator stops and/or ramps to limit number of stairs required for personnel in SCAPE suits. Allow 44" minimum width for walkways. Consider suited personnel in the design and placement of the control panel, hypergol lines, signs, displays, equipment labels. Enlarge work platform at vehicle interface to provide space to set tools down	
Visual access – lighting (by OSHA requirements).	Provide lights on the access platforms.	
Hypergol Servicing Systems		
Work envelope – access arm at vehicle interface to accommodate at least two SCAPE personnel and control panel.	Provide adequate space on access arm to allow SCAPE personnel maneuverability. Include SCAPE technicians on the design team.	
Connectors – quick disconnects vs. B-nuts.	Perform formal usability analysis in SCAPE lab as part of connector trade study.	
Damage/error prevention – fundamentally different hypergol servicing approach without the level of redundancy and controls used by the Shuttle system.	Perform an in-depth task analysis of hyper servicing (HF-PFMEA, socio-technical PRA, or other method). Proactively identify and mitigate potential process escapes, process catches, and human errors.	
Lifting, pushing, and pulling – weight/size of servicing equipment and effort required to move/maneuver the equipment.	Consider hoist or rail crane to assist with equipment lifts. Include lift points. Minimize number of cables and hoses in higher traffic areas on the platform.	

3. DESIGN TEAM RESULTS AND RECOMMENDATIONS

3.1 Design Team Results

Tables 1a and 1b are only a very small sampling of entries in 5 of the 9 Design Team worksheets. The completed set of worksheets was far more extensive, but they were never intended to be comprehensive assessments. Rather, they were intended to provide Design Teams examples and a process for thinking about human factors issues with respect to their GS/GSE designs. The workbook provided greater detail on each issue as well as additional human factors tools and resources. The mostly volunteer core team was not able to become embedded members of Design Teams themselves but attended some design reviews and continue to advocate for the infusion of human factors into the Ground Operations Planning document, volume 3, CxP 72149-03, a new KSC GSE Design Handbook, and to support updates to the NASA design standards for ground support equipment (NASA STD 5005) and facility systems (NASA STD 512) and the development of a KSC Human Factors Handbook. They have discussed the exchange of best practices and lessons learned with the Lockheed Martin/USA group designing GSE for Orion assembly & processing and the engineering and human factor organizations at Johnson Space Center (JSC).

3.2 Recommendations

Following the November activities, the core team compiled all of the notes and inputs to make a final worksheet for each of the Design Teams. This was handed off to the Team Lead so they could keep these results close at hand while their designs progressed. On the basis of final results and feedback from the Team Leads, a set of recommendations were developed in four main areas: 1) the utilization of technician experience and expertise, 2) the integration of human factors engineering into the systems engineering process, 3) the need to address human factors in software and computer systems design, and 4) to increase the use of modeling and simulation capabilities.

Utilize technician experience and expertise, as appropriate. This recommendation recognized the current existence of safety and operational knowledge from Safety and Mission Assurance and Operations Engineering organizations. It is important to continue soliciting their design inputs.

Integrate human factors engineering into the systems engineering process. This recommendation recognized the need to go beyond single patch solutions by establishing a human factors point of contact in Engineering organizations to provide consistent and sustained human factors support for GS/GSE Design Teams. Ideally, their responsibilities for immediate implementation would include:

- Track and help resolve significant human factors issues, including those identified during the Pathfinder Activity
- Lead development of the Human Factors chapter (and associated references) in the Engineering Design Handbook
- Provide human factors support to selected Design Teams

In the longer term, the following recommendations were made:

- Acquire additional human factors expertise to provide embedded support to Design Teams, including completion of Human Factors assessments and requirement verifications
- Determine criteria for a complete, valid Human Factors assessment

A Human Factors assessment is currently a required work product in the Technical Review Process and while the evaluation worksheet completed during the Pathfinder Activity was could help serve this functions, it was not designed to satisfy this requirement. More development is needed to establish Human Factors assessment methods and approaches that are applicable across the range of GS/GSE complexity, criticality, hazards, types of crew/GSE interfaces, etc.

Address the need for adequate consideration/evaluation of human factors in software and computer system designs. Existing NASA initiatives begin to address this issue, including the NESC Academy Human Factors course modules on Control Center Design, and Design & Analysis of Human-Computer Interaction Process. But the knowledge and expertise needs to reach the designers in a relevant and effective timeframe.

Increase the use of modeling and simulation capabilities for evaluating designs from a human factors perspective. Again, there are existing NASA capabilities and new projects that can be leveraged.

4. SUMMARY

A team of human factors researchers and practitioners developed an approach to incorporate human factors considerations into the design of Ground Systems and Ground Support Equipment. Materials were developed to conduct a Human Factors Overview that provided an introduction to human factors principles and a preview to the issues that would be discussed in the individual Design Team sessions to follow. A workbook and worksheet were developed to provide additional resources and a guide for applying human factors issues to their specific designs. Nine teams whose mechanical, fluid and electrical designs were nearing the 30% design review, participated and completed worksheets that identified a wide variety of human factors challenges and potential solutions.

This Pathfinder Activity clearly demonstrated that embedding human factors expertise into Design Teams is useful and appreciated, and several human factors enhancements have been baselined in design packages. The Engineering organization is currently developing short and long term Human Factors Plans and there has been increased recognition of the importance of ground crew factors in NASA standards and Constellation Program requirements. Our expected long term outcome is improved operability: ground systems that are safer and easier (and therefore cheaper) for ground crews to operate and maintain over 20+ years of launch operations.

5. REFERENCES

1. Strang, N. *Ground Systems Testing*. Crosslink, Retrieved October 9, 2008, from www.aero.org/publications/crosslink/fall2005/07.html

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